Analysis and Modeling of Ocean Acoustic Fluctuations and Moored Observations of Philippine Sea Sound-Speed Structure

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LONG-TERM GOALS

The long-term goals of this research are to understand the statistics of acoustic fields in both deep and shallow water ocean environments.

OBJECTIVES

The primary objective of this work is the development of accurate, and computationally efficient, reduced-physics acoustic propagation models for the prediction of the statistics of ocean acoustic signals in both shallow and deep water environments. Examples of acoustic field statistics of interest are mean intensity, coherence, and intensity variance. The focus here will be primarily on the Philippine Sea, and the SW06 site off the New Jersey coast, since these are the most recent and complete data sets. Reduced physics models are important to ocean acoustics not only because they are often computationally efficient but also because they elucidate what scales of the ocean can have the maximum impact on the acoustical field. This knowledge allows for more focused study on those oceanographic processes that will have large acoustical influences. Therefore centrally related to the primary objective of this research will be an effort to characterize ocean sound speed variability, and develop ocean models that can be easily assimilated into acoustic fluctuation calculations. In the Philippine Sea, models of eddies, internal tides, internal waves, and fine structure (spice) will be needed, while in the shallow water case a model of the random linear internal waves is lacking.

APPROACH

The approach taken here is to first test our reduced physics models against Monte Carlo simulation, and then once the scattering physics is understood, apply the models to observations. This approach was successfully used in developing a model for mode coupling caused by shallow water nonlinear internal waves (Colosi, 2008). Two different theoretical approaches will be considered. The first is a coupled mode technique originally described by Creamer (1996) and further developed by our group (Colosi and Morozov, 2009), and the second approach is a hybrid path-integral/geometric ray approximation for coherence properties along a time resolved wavefront.

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In our analysis of ocean sound-speed structure we are utilizing observations from the 2009 Philippine Sea field trial and from the SW06 experiment. In these experiments moored seabird temperature, conductivity, and pressure sensors, as well as ADCPs were placed on multiple moorings giving vertical, temporal, as well as geographic information concerning ocean fluctuations. These data are being used to characterize internal tides, mesoscale eddies, stochastic Garret-Munk type internal waves, and intrusive finestructure (spice).

WORK COMPLETED

Work completed in the previous year has focused on analysis of the Philsea 09 and SW06 oceanographic data sets and Monte Carlo testing the coupled mode model for all second moments of the acoustics field.

RESULTS

A. Coupled Mode Theory: Deep Water Coherence

Based on the work of Creamer (1996), Andrey Morozov and I have developed a coupled mode theory that can very accurately predict cross mode coherence functions which are used for important acoustical second moments like field coherence and mean intensity (Colosi and Morozov, 2009). The theory assumes small angle multiple forward scattering and that the Markov approximation is valid. Regarding the environment the theory assumes that the ocean sound speed structure is dominated by a random superposition of internal waves, like those described by the Garrett-Munk (GM) internal wave spectrum. The range evolution of the cross mode coherence function $\langle a_{n1} a_{p2}^* \rangle(r)$ for separations between points (1) and (2) is given by

$$\frac{d}{dr}\langle a_{n1} a_{p2}^* \rangle = i(l_{n1} - l_{p2}^*)\langle a_{n1} a_{p2}^* \rangle - \sum_{m=1}^{N}\sum_{q=1}^{N}\langle a_{q1} a_{p2}^* \rangle I_{mn1,qm1} - \langle a_{m1} a_{q2}^* \rangle I_{mn1,qp2}^* - \langle a_{q1} a_{m2}^* \rangle I_{mp2,qn1} + \langle a_{n1} a_{q2}^* \rangle I_{mp2,qm2}^*$$

where $l_n = k_n + i\alpha_n$ is the complex mode wavenumber, and $I_{mn,pq}$ are scattering matrices which involved the spectrum of internal waves. The points (1) and (2) could involve separations in time, horizontal position, or frequency. In our work we have analytic forms for the scattering matrices for idealized internal wave spectra, as well as numerical methods for general internal wave spectra. For the case of time and frequency separations the scattering matrices are independent of range and the evolution equation is easily evaluated numerically. For horizontal separations the matrices depend on range but still can be evaluated numerically. Importantly, the cross mode coherence is central to predicting the coherence function given by

$$\langle p(r_1,\omega_1,t_1)p^*(r_2,\omega_2,t_2)\rangle = \sum_{n=1}^{N}\sum_{p=1}^{N}\frac{\langle a_{n1} a_{p2}^*(r)\rangle}{r}\frac{\phi_{n1}(z_1)\phi_{p2}(z_2)}{\sqrt{k_{n1}k_{p2}}}$$

where $\phi_n(z)$ are the depth eigenfunctions of the unperturbed problem. Monte Carlo numerical simulations in a deep water environment with GM internal wave induced sound speed perturbations have been carried out and comparisons were made between the temporal coherence computed from the

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simulations and predictions from the theory: These comparisons are shown in Fig. 1. In this case a 100-hz point source on the sound channel axis is simulated and the agreement between theory and Monte Carlo simulation is excellent. While significant mode coupling is occurring in this case, Fig. 1 also shows that the temporal coherence is strongly influenced by adiabatic effects. We anticipate these results to be equally good in shallow water environments. Codes exist to compute coherence for horizontal separations and across frequency

B. Coupled Mode Theory: Shallow Water

The evolution equation for the cross mode coherence can also be used to better understand shallow water problems (Colosi, 2008). Taking an 80-m downward refracting shallow water waveguide with bottom attenuation of 0.5 dB/λ, bottom density of 1900 kg/m^3, bottom sound speed of 1650 m/s, Monte Carlo simulations with GM internal waves (j*=1) were computed and estimates of mean intensity from the simulation and the theory were compared. The upper panel of Fig. 2 shows the comparison at 400 Hz for a point source at 70-m depth. The theory is seen to accurately represent the Monte Carlo simulation to within a fraction of a dB (nearly identical results are also seen at 200-Hz). Importantly the theory shows that cross mode coherences can decay quite rapidly in this shallow water environment (See Fig. 2 where mean intensity shows very little oscillations with range). The decay of cross mode coherences, and the phase randomization of the modes has important consequences regarding the interaction of sound with nonlinear internal solitary waves (ISW), as that interaction depends critically on the relative phases of modes at the ISW (Colosi, 2008; Preisig and Duda 1997). The lower panel of Fig.2 demonstrates this effect, where the mean intensity with and without solitons is presented (the modeled solitons have a 20 m/s sound speed perturbation). It is seen that near the solitons the mean intensity is not terribly different from the calculation without the solitons, and after the solitons memory of the soliton packet is quickly lost. These results have been written up in a manuscript to be submitted for the JASA special issue on SW06 (Colosi, Duda, and Morozov 2010).

C. Analysis of SW06 Oceanographic data

During the SW06 experiment, a mooring of 10 pumped Seabird microcats were deployed on a mooring to quantify the space time scales of sound-speed variability due to internal waves and spicy thermohaline structure. Data were collected between July 31 and September 4, 2006 thus giving slightly over a one-month record. The data were processed over the last year and a manuscript has been written to be submitted to the JASA special issue on SW06 (Colosi et al 2010). Basic results from this paper are:

1. By analyzing along isopycnals internal waves were separated from spicy thermohaline structure.
2. Frequency and vertical mode number spectra for the random internal wave field, and the internal tide, were estimated.
3. Frequency spectra and vertical covariance functions were estimated for the spicy sound speed fluctuations.
4. Using rms sound speed as a metric the spicy fluctuations were found to dominate the variability, followed by (in order) nonlinear internal waves, random internal waves, and lastly internal tides (See Figure 3).
5. Surprisingly the internal tide was observed to have a rather rich vertical structure with significant energy in the first three modes.

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D. Analysis of the 2009 Philippine Sea Oceanographic data.

During the 2009 Philippine Sea field test, 30 Seabird microcats and microtemps, as well as ADCP's were deployed on each of the source and receiver moorings in order to quantify the space-time scales of sound-speed variability. Data were collected between April 5 and May 9, 2009 thus giving slightly over a one-month record. The data have just recently been processed and some preliminary results are available. Basic results from this analysis are:

1. By analyzing along isopycnals, internal waves were separated from spicy thermohaline structure.
2. Spectra for internal waves were estimated showing random internal waves and strongly nonlinear diurnal and semidiurnal internal tides.
3. Using rms sound speed as a metric is sound that random internal waves and the internal tide have roughly equal contributions to the sound speed variation. Spicy effects are found to be quite small, except for near the mixed layer.
4. Analysis of vertical covariance functions and estimation of internal wave mode spectra is underway, but incomplete at this point.

IMPACT/APPLICATIONS

There are several implications of this work to the understanding of acoustic predictability. A short list of the major issues/impacts are given below.

1. Many observations and numerical studies have shown that internal wave induced sound speed perturbations have a large effect on mean intensity (transmission loss) in both shallow and deep water environments. The coupled mode theory developed by our group could conceivably be used as a Navy model for predicting low frequency mean TL and coherence.
2. The SW06 sound speed fluctuation analysis shows that spicy sound speed structure dominates the fluctuation field. The shallow water community needs to explore the acoustic propagation implications of this result.
3. The computational result that shallow water random internal waves can dramatically modify the acoustic interaction with nonlinear solitary-like waves is a compelling result, and warrants further exploration with observations.
4. The high quality Philippine Sea 2009 oceanographic data set has allowed for a definitive separation of internal-wave induced sound-speed perturbations and those caused by finestructure or spice. With this information ocean models could be constructed that separately treat internal waves and finestructure.
5. The Philippine Sea 2009 oceanographic data set will also allow the construction of a regional internal tide model: the relative important of internal tides to acoustic variability, however, is yet to be determined.

TRANSITIONS
None

RELATED PROJECTS
None

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PATENTS
None

HONORS/AWARDS/PRIZES

A. B. Wood Medal for "significant contributions to the understanding of acoustic scattering by internal waves in long-range propagation".
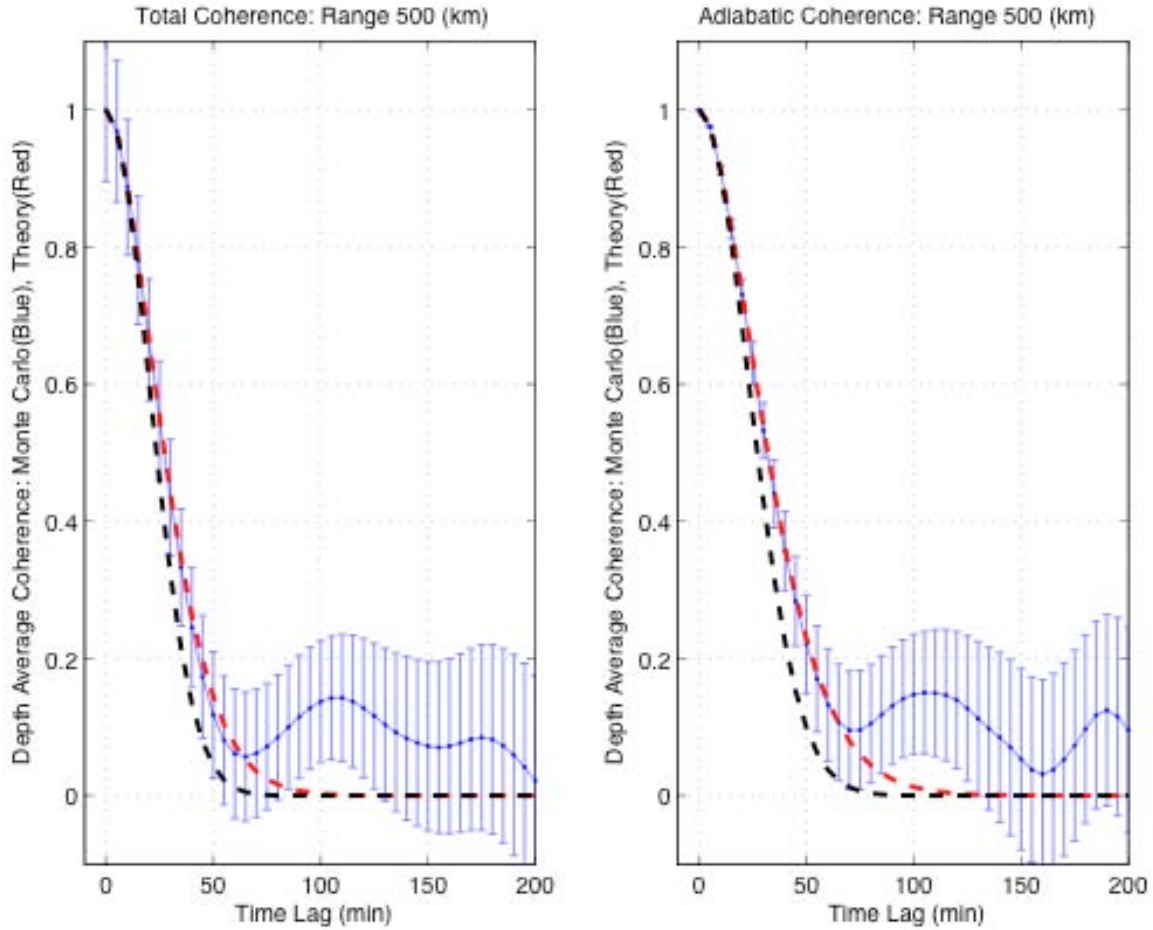

Figure 1: Monte Carlo Simulation (Blue) and theory prediction (Red) of depth averaged time coherence for 100 Hz sound propagation through random fields of GM internal waves. The black curve shows the theoretical prediction if a quadratic expansion is done with regards to the time lag.
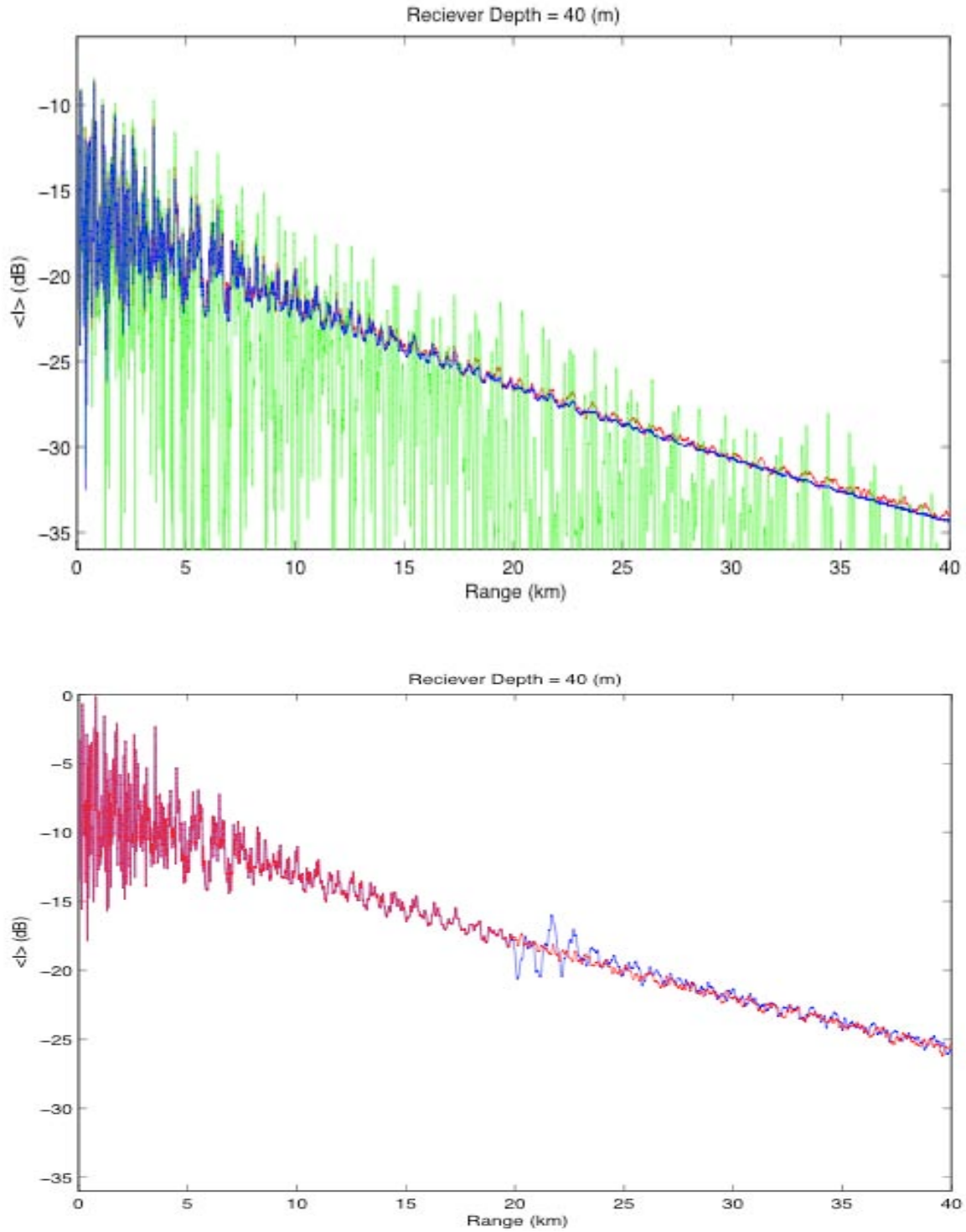
Figure 2: Upper panel: Monte Carlo Simulation (Red) and theory prediction (Blue) of mean sound intensity for 400 Hz sound propagation in shallow water through random fields of GM internal waves. The lower panel shows Monte Carlo simulations of propagation through GM internal waves (Red) and GM internal waves plus a large 3 wave soliton packet at 20-km range (Blue).
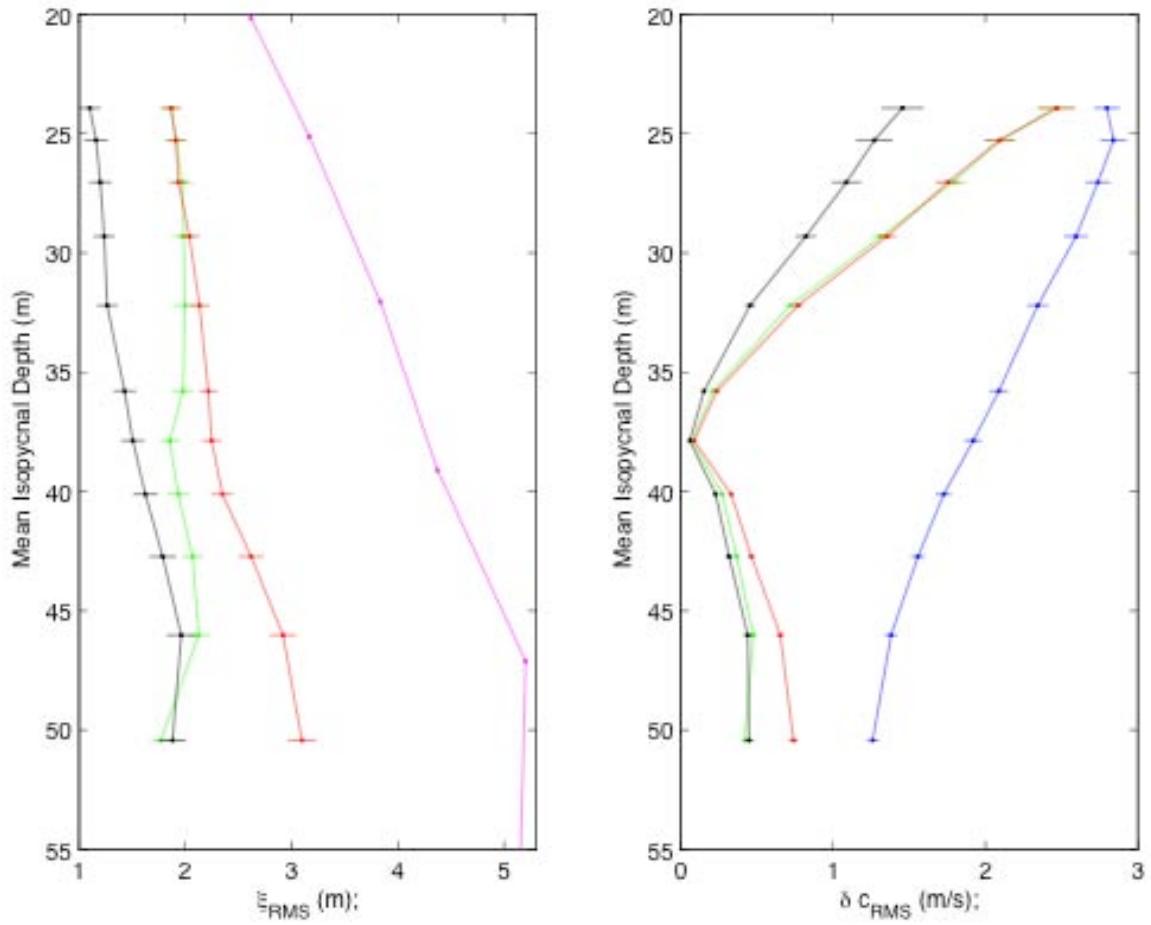
Figure 3: RMS displacement (left panel) and sound speed (right panel) statistics from the SW06 observations. Horizontal lines correspond to rms estimation uncertainties. Black curves correspond to internal tides, green curves are for nonlinear internal waves, and red curves are for the random internal wave field. The magenta curve on the left is from a WKB depth scaling. The blue curve on the right-hand side is the rms sound speed from spice in the frequency band between the maximum buoyancy frequency and the Coriolis frequency.